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Life-cycle assessment of a photovoltaic system in Catalonia (Spain)

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ABSTRACT

The life-cycle analysis (LCA) of photovoltaic (PV) systems is an important tool to quantify the potential environmental advantage of using solar technologies versus more traditional technologies, especially the ones relying on non-renewable fossil fuel sources.

This work performs a life-cycle assessment on a 200 kW roof top photovoltaic (PV) system with polycrystalline silicon modules and evaluates the net energy pay-back and greenhouse gas emission rates. The performed life-cycle assessment "upstream" and "downstream" processes are considered, such as raw materials production, fabrication of system components, transportation and installation. The energy pay-back time ratio is determined for the installed technology and two other technologies of PV modules (monocrystalline and thin-film).

The analysed PV system, located in Pineda de Mar (Catalonia, Spain), has an energy pay-back time ratio of 4.36 years. Furthermore, a sensibility analysis on solar radiation has been performed.

Contents

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1. Introduction

Photovoltaic energy conversion is widely considered as one of the more promising renewable energy technologies which has the potential to contribute significantly to a sustainable energy supply and which may help to mitigate greenhouse gas emissions [10].

Photovoltaic (PV) modules, made of multiple interconnected PV cells of semiconducting materials, convert solar light photons into electricity [1–6,59]. When sunlight hits the modules, photons with a certain wavelength trigger electrons to flow through the materials to produce direct current (DC) electricity [4,6]. Commercial PV materials commonly used for photovoltaic systems include monocrystalline, polycrystalline [7,8] and amorphous silicon and thin film technologies [1–14].

A typical PV system consists of the PV module and the balance of system components (BOS) [15], which includes the structures for mounting the PV modules and the power-conditioning equipment for converting the generated DC electricity to alternate current (AC) with the proper form and magnitude required by the power grid [1,6,16].

The production technology for photovoltaic power plants has constantly been improved over the last decades, e.g. for the efficiency of cells, the amount and production processes for the silicon required, and the actual capacity of production processes [17].

Over the two last decades a number of detailed studies on energy requirements of PV modules or systems have been published [4,5,8–10,18–22]. A vast number of authors from the European Union [4,8–13,18,23–26], the USA [1,5,6,11,27,28], Australia [16], Brazil [1], India [2,29], Singapore [30], Japan [31], etc., have focused on the environmental aspect of future photovoltaic (PV) systems which are assessed through life cycle analysis (LCA), considering mono- and polycrystalline silicon cells, amorphous and ribbon-silicon, CdTe and CIS thin film cells. Most of these studies were concerned with production processes; and their environmental impact assessment was commonly performed from cradle to gate, evaluating the net energy ratio (NER), the EPBT and greenhouse gas emissions, and therefore their mitigation.

Hagedorn [19,32], a pioneer in the field of LCA, extensively analysed material and energy flows in silicon solar cell production facilities in Germany around 1990, covering prototypes of crystalline and amorphous silicon module technologies. Because of its thoroughness and extensive documentation, his work formed the basis for many later studies and, in fact, it was the underlying dataset for the ExternE – (External Costs of Energy) projects – analysis of PV systems [33]. The main aim of the ExternE research projects was to develop a methodology to calculate the external costs caused by energy production and consumption. Later studies partially updated Hagedorn's data on silicon yields and energy consumption [20,32,34–37].

In the past years, the PV sector developed rapidly. Ongoing projects such as *CrystalClear* [38] have investigated the up-to-date life cycle inventory data of the multi- and monocrystalline technologies [13]. CrystalClear was one of the first Integrated Projects to be carried out in the 6th Framework Program of the European Union. The project ran from January 2004 to December 2008 [38]. The aim was to improve the environmental quality of the modules and the corresponding systems, decreasing the energy pay-back time of photovoltaic systems and the CO_2 emissions. Moreover, CrystalClear aimed to reduce the environmental impacts of PV modules. This strengthens the position of PV as a clean generator of electricity [38].

In Spain, De la Hoz et al. contributed a critical view of the development of grid-connected photovoltaic systems (GCPVS) during the period 1998–2008 by looking into the different actions that were intended to promote this technology [39]. They also made a special case of the particular promotion of PV systems on roof and goes further to analyse how these actions have affected GCPVS evolution as well as the magnitude of their impact on its performance [39].

Bayod-Rújula et al., described some useful parameters to assess the technology and distribution of modules to be installed in flat roofs and terraces of buildings in Spain, as well as they analysed the effect on the energy parameters of the modules tilt and disposition through a case study, considering different technologies [40].

Concerning to life-cycle analysis in Spain, García-Valverde et al. [41] has assessed, energetic and environmentally, a 4.2 kWp stand-alone photovoltaic system (SAPV) at the University of Murcia (south-east of Spain) in 2009. They found the energy pay-back time and the specific CO_2 emissions, and compared the results with other supply options (diesel generator and Spanish grid) [41].

2. The life cycle approach

Traditional environmental impact analyses generally focus on a restricted number of life cycle steps. This approach is very narrow because it gives only a restricted picture of the effective environmental performances of the product [42]. Furthermore, in renewable energy plants generally the largest environmental impacts occur during the manufacture and installation steps [42].

The life cycle assessment (LCA) is a methodology able to investigate every direct and indirect impact throughout the life cycle steps of products or services [2,17,32,42–44]. The goal of a LCA is to quantify material and energy resource inputs as well as waste and pollutants outputs in the production of a product or service [1]. The method attempts to systematically quantify the environmental effects of the various stages of a product or process life-cycle: materials extraction, manufacturing/production, use/operation, and ultimate disposal (or end-of-life) [1]. This approach is typically used to compare the environmental impacts for different products performing the same functions [42,45,46]. The LCA is today well defined and also regulated by the international standard series ISO 14040 [18,42,44,46–54], which is divided into 4 steps: goal and scope definition, inventory analysis, impact assessment and interpretation [17]. The results of a life-cycle study applied to a renewable plant can be of great relevance for various aspects [42,46]:

- To compare performances of different system technologies.
- To locate system's components or sub-processes responsible of the highest environmental impacts (hot spots).
- To have useful information in order to reduce the environmental impacts and improve plant's performance.

The construction of the power facilities is an important part, especially in the wind and solar energy, and hence it should be included as part of the required input. When performing a LCA it is a good practice to define proper system's boundaries and a cut-off threshold for impact assessment [8,10]. The analysis should include a detail of all the materials and components employed throughout the life-cycle. The life-cycle analysis was performed from the extraction of the raw materials to the installation of the system and commissioning [6,9,46].

2.1. Environmental indexes

The most frequently measured life-cycle metrics for PV system environmental analyses are the energy payback time (E_{PTB}) and the greenhouse gas emissions [6,55].

As depicted in Eq. (1), the energy payback time (E_{PBT}) is defined as the period required for the PV system to generate the same amount of energy that was used to produce the system itself

Table 1
CO_2 emissions and E-PBT of PV systems.

Author	Year	Characteristics	Emissions of CO_2 (gCO_2/kWh)	E-PBT (years)
Alsema [1]	2000	Monocrystalline grid connected roof top systems—insolation of 1700 kWh m^{-2} year^{-1}—30 year lifetime	60.0	3.2
Alsema [1,9]	2000	Thin film (amorphous) grid connected roof top systems—insolation of 1700 kWh m^{-2} year^{-1}—30 year lifetime	50.0	2.5–3
Alsema [6]	2000	Polycrystalline 13% efficiency—insolation of 1700 kWh m^{-2} year^{-1}	46.0	2.5
Alsema [6]	2000	Monocrystalline 14% efficiency—insolation of 1700 kWh m^{-2} year^{-1}	63.0	3.1
Greijer [1]	2000	500 MW power plant—amorphous technology—efficiency = 7%—process energy = 100 kWh/m^2—20 year lifetime Expected output = 2190 kWh m^{-2} year^{-1}	19.0	n.a.
Greijer [1]	2000	Efficiency = 12%—process energy = 220 kWh/m^2	22.0	n.a.
Oliver [1]	2000	Centralized plant 12% module efficiency polycrystalline	170.0	n.a.
Nomura [1]	2001	Concentration design using a polycristalline solar cell grid connected—short run technology	133.0	n.a.
Australian Coal Association research programmes (ACARP) (Australia) [6,11]	2001	n.a.	100.0	n.a.
Gagnon and Uchiyama [1]	2002	n.a.	13.0	9
Meier [1]	2002	Building integrated PV system	39.0	3.5–6.3
Ito [1]	2003	Polycrystalline 12.8% efficiency	44.0	1.7
European Commission, ExternE (Germany) [6,11]	2003	n.a.	180.0	n.a.
Jungbluth [6]	2005	Polycrystalline 13.2% efficiency—insolation of 1100 kWh m^{-2} year^{-1}	39.0–110.0	3–6
Jungbluth [6]	2005	Monocrystalline 14.8% efficiency—insolation of 1100 kWh m^{-2} year^{-1}	39.0–110.0	3–6
Fthenakis and Alsema [11]	2005	Polycrystalline—roof top PV systems under an insolation of 1700 kWh m^{-2} year^{-1}—efficiency = 13.2%	37.0	2.2
Fthenakis and Alsema [11]	2005	Monocrystalline—roof top PV systems under an insolation of 1700 kWh m^{-2} year^{-1}	45.0	2.7
Alsema and de Wild-Scholten [12]	2005	Ribbon silicon—roof top system under an insolation of 1700 kWh m^{-2} year^{-1}—30 year life time—efficiency = 11.5%	30.0	1.7
Alsema and de Wild-Scholten [12]	2005	Polycrystalline—roof top system under an insolation of 1700 kWh m^{-2} year^{-1}—30 year life time—efficiency = 13.2%	35.0	2.2
Alsema and de Wild-Scholten [12]	2005	Monocrystalline—roof top system under an insolation of 1700 kWh m^{-2} year^{-1}—30 year life time—efficiency = 14%	45.0	2.7
Kannan et al. [2]	2006	Monocrystalline roof top system—25 year life time—efficiency = 10.6%	165.0	4.5
Muneer et al. [2]	2006	Monocrystalline roof top system—30 year life time—efficiency = 11.5%	44.0	8
Pacca et al. [2]	2007	Amorphous PV system—20 year life time—efficiency = 6.3%	34.3	3.2
Pacca et al. [2]	2007	Polycrystalline modules—20 year life time—efficiency = 12.92%	54.6	7.5
Wild-Scholten and Schottler [56]	2008	Thin film PV roof top system—Crystalline Si 2006	30.0	n.a.
Sinke et al. [57]	2009	On roof installation—crystalline silicon—insolation of 1700 kWh m^{-2} year^{-1}	30.0	1.8

n.a.: not available.

[6,9,10,16,38] including the energy needed for manufacturing, set into motion, maintaining and decommissioning the entire system:

$$E_{PBT} = \frac{E_{input}}{E_{output}} \tag{1}$$

The emissions of criteria pollutants during the life cycle of a PV system are largely proportional to the amount of fossil fuel burned during its various phases, in particular PV material processing and manufacturing. Toxic gases and heavy metals can be emitted directly from the material processing and PV manufacturing, and indirectly from generating the energy used at both stages. Accounting for each of them is necessary to create a complete picture of the environmental impact of a technology [6].

2.2. Environmental performances of photovoltaic systems

Although several published life cycle assessments (LCA) quantify the life cycle energy input of PV installations and their environmental releases, such as CO_2 emissions, normalized by electricity output, these studies are difficult to compare [5].

Different studies use different methods, with different boundary conditions, rely on different data sources and inventory methods, model different PV technologies at different locations, and consider different lifetimes and analytical periods [5]. Thus, the range of values published is quite large. Table 1 shows a compilation of studies that quantified CO_2 emissions and E-PBT of PV systems [1,2,9,11,12,55–57]. Variability in the results may be linked to the boundary setting of each analysis, energy mix used in material manufacturing in each system, and also differences in production processes used to manufacture the PV system. Because different PV technologies have different energy conversion efficiencies, this aspect of PV systems also affects the final results of the assessment.

3. Case study of a photovoltaic system in Catalonia, Spain

This section presents the different life cycle stages considered in the realization of a LCA applied to a representative case study: a photovoltaic system located in Pineda de Mar (Catalonia, Spain).

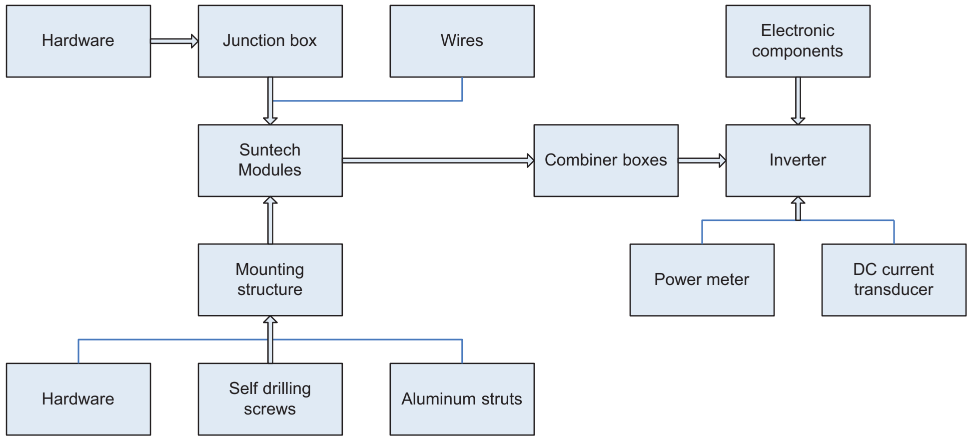

Fig. 1. Level diagram of balance of the system (BOS) components.

The data regarding the installation, use and maintenance phases have been provided by the project design technicians and the local electrical company; and the data regarding the manufacturing of the components refers to average European data and was modelled using SimaPro 6.0 [2,8].

The comparison of the system performance is assessed based on a per kWh functional unit [46]. That is, the life cycle energy and material inputs in the system and the respective quantified environmental emissions are normalized based on the total expected electricity output of the system after considering the conversion losses such as the use of the inverter.

3.1. Photovoltaic system: general framework

The case study is located in the North-East of Spain and covers a global surface of 1649 m^2.

The facilities consist of a roof integrated, grid connected system without solar tracking. The plant includes 850 polycrystalline technology modules (50 parallel arrows of 17 serial connected modules) and has a rated power of 200 kWp.

The study has assessed the following life-cycle steps:

- Manufacturing of photovoltaic modules, inverters and support structures.
- Erection of building structures and ancillary facilities (cables, transformers, etc.).
- Transport occurring during each phase.

3.2. Manufacturing of the main components

The inventory of life cycle energy and material inputs in the production of a Suntech STP-270 module was based on two previous studies related to the manufacturing of a generic polycrystalline module. Phylipsen and Alsema (1995) [8] reported the material composition (kg/m^2) and process energy requirements (kWh/m^2) for the manufacturing of a single polycrystalline module in Europe [8]. The functional unit of that assessment is on a per m^2 basis. After calculating the material mass per module the materials are then modelled in SimaPro. Although it is assumed that the Suntech STP-270 modules are produced in China, the energy (electricity) requirements for the module were modelled in SimaPro using the EU average electricity fuel mix. Only materials with more than 1% of weight per kg have been considered.

Material input for the aluminium frame was calculated based on the AutoCAD diagrams for the Suntech STP-270 module. The aluminium mass was modelled in SimaPro based on the aluminium with 25% of recycled content from the BUWAL LCI database.

The balance of the system (BOS) [16] comprises the structures and equipment required for supporting the modules and delivering the electricity to the local network [1]. The BOS consists of the junction boxes attached to the back of each module, wires, and the aluminium mounting structures. In addition, there are other aluminium parts: T shaped connectors and inside bar connectors. Fig. 1 shows the level diagram of balance of the system (BOS) components including structural and electronic components.

The materials data for the inverter bill were collected directly from the company. The inverter manufacturer included structural components, printed circuit boards, some electronic components, wiring materials, nuts/bolts, packaging and transportation.

3.3. Installation and buildings

The installation consists of the modules transportation from the factory to the installation site and their installation on to the roof of the building.

The total weight of the polycrystalline modules was 19,550 kg. The total weight hoisted from the ground level to the roof of the building was approximately 20,000 kg. The equipment used was a Sterling truck with a Terex hoist (TC 4792). The truck was powered by a caterpillar engine (CAT 3126), and the performance of the engine during the hoisting of the packages was surveyed. The total working time was approximately 5 h and the estimated energy consumption was approximately 20,000 MJ.

3.4. Transports

The modules were transported in a ship coming from Shanghai to Barcelona. The distances were obtained from Google Maps™ with the total distance travelled being 10,092 km.

The transportation of the inverter from the Shanghai production facility to Pineda de Mar (Catalonia) was also modelled using data for the ship from the ETH-ESU database in SimaPro.

3.5. Power and solar radiation availability

The amount of electricity produced by a PV system is directly proportional to the amount of solar radiation received by the arrays, which depends on the module's position relative to the sun. Solar beams reaching the module perpendicular to its surface are the most effective ones. Therefore, positioning the module in order to maximize the amount of solar radiation received perpendicular to

Table 2
Breakdown of the required energy for the preparation of the whole system.

System components	Energy input [MJ]	% of total energy [%]
Suntech STP-270 modules	4.59×10^6	84%
Transportation	6.60×10^5	11%
Balance of System	10.96×10^4	3%
Installation	8.96×10^4	2%
Inverter	3.02×10^4	1%
Total	5.47×10^6	100%

Table 3
Primary energy consumption per area.

Module model	Primary energy per module [MJ]	Area per module [m^2]	Energy/area [MJ/m^2]
Suntech STP-270	5400	1.94	2783.50

Table 4
Primary energy consumption per peak power.

Module model	Primary energy per module [MJ]	Power per module [Wp]	Energy/peak power [MJ/Wp]
Suntech STP-270	5400	270	20

its surface is fundamental for maximizing the electrical output of the array.

The installation was analysed with PVsyst,[1] a PC software package for the study, sizing, simulation and data analysis of complete PV systems. A PVsyst model was created in order to quantify the amount of solar radiation. It calculates the available solar radiation over discrete time intervals during a year for a given location and date. In addition, the meteorogical reference Meteonorm 6.1 (Edition 2009), incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location has been used for obtaining meteorological data needed.

With the tilt angle regarded, the annual solar radiation received and modules and inverters efficiencies, PVsyst generates an expected output production of 282,014 kWh/year.

4. Case study

This section presents the results of a LCA applied to a representative case study which is a photovoltaic system located in Pineda de Mar (Catalonia, Spain).

4.1. Energy analysis

The total primary energy consumption of the PV system was 4.59×10^6 MJ. Table 2 introduces the breakdown of the energy input into the system and the percentage of total energy consumed by every component. Out of the total primary energy consumption of 5.48×10^6 MJ, 84% (4.59×10^6 MJ) was for the production of the PV modules.

Table 3 introduces the primary energy consumption per area (m^2) for the PV modules used. The energy for the polycrystalline modules was obtained from previous research literature [8,10].

Table 4 introduces the primary energy consumption per peak power (Wp) for the photovoltaic modules used.

[1] URL: http://www.pvsyst.com/5.2/index.php.

4.2. Environmental analysis: air pollutants and greenhouse gases emissions

Table 5 introduces the mass of criteria air pollutants and greenhouse gases released at every stage of the PV system life cycle and its major components.

For the criteria air pollutants, the production of the photovoltaic modules contributed to 65% of the carbon monoxide emissions with the other significant contribution occurring during the transportation stage. The production of the photovoltaic modules also contributed to 99%, 95%, 70% and 65% of PM_{10}, SO_2, lead and hydrocarbons, respectively. The installation and transportation stages contributed to 26% of NO_X with the remaining NO_X emissions occurring during the production of the photovoltaic modules. The photovoltaic modules also contributed to 90% and 75% of the CO_2 and methane emissions, respectively. Thus it is evidently clear that except for NO_X, the production of photovoltaic modules emit the highest amount of air emissions among all life cycle stages.

4.2.1. Environmental footprint of the modules

The ecological footprint method evaluates the land area impacts exerted by the resource-energy consumption and greenhouse gas emissions associated with a process. In order to convert the release of CO_2 from a process, the molar carbon fraction (12 g of C per 44 g of CO_2) is applied. Furthermore, using the factor of 1.8 metric tons of carbon/hectare/year [58] the land area required for the assimilation of CO_2 emitted from a process is determined (Table 6). This means that an average forest area of one hectare can sequester 1.8 metric tons of carbon per year. In essence 10,000 m^2 (a hectare) of forest area is thus used to sequester 1.8 metric tons of carbon emitted from a process or service. In this study we calculated the land area impacts exerted during the manufacturing of PV modules (due to the release of CO_2), added that value to the actual amount of land area (roof of the building) occupied by the PV modules. However, that area was not considered in the analysis due to resource extraction such as mining.

4.3. Comparison between the used technology (polycrystalline) and the two other ones (monocrystalline and thin film)

4.3.1. Required area for the different modules in a 200 kWp system

The Wp/m^2 ratio is depicted in Fig. 2 which shows the installation total area for the three photovoltaic modules technologies (excluding the required area).

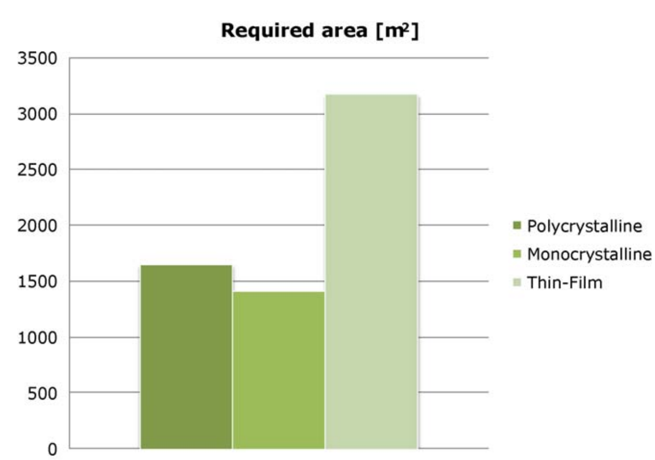

Fig. 2. Required area for a 200 kW PV installation.

Table 5
Air pollutants and greenhouse gas emissions of the PV system.

	Units	STP-270	BOS	Installation	Transport	Inverter	Total
Air pollutants							
Nitrogen oxides	kg	1287.62	14.42	474.54	4.66	20.9	1802.12
Sulfur oxides (SO_2)	kg	2755.65	46.78	39.75	20.42	27.51	2889.66
Carbon monoxide (CO)	kg	369.58	2.58	144.84	10.26	19.63	546.89
Particulate matter (PM_{10})	kg	57.12	0.60	0	0	0	57.72
Lead (Pb)	kg	8.9×10^{-2}	1.14×10^{-6}	1.08×10^{-3}	3.50×10^{-2}	6.84×10^{-3}	0.13
Hydrocarbons (HC)	kg	343.42	11.75	165.03	3.2	18.12	541.52
Greenhouse gases							
Carbon dioxide (CO_2)	kg	246361.9	6727.2	7901.3	1762	4054	266806.4
Methane (CH_4)	kg	756.19	240.60	32.12	3.86	10.06	1042.8

Table 6
Total area required for the PV system.

Total CO_2 emissions [Tm]	Ratio [m^2/Tm]	CO_2 assimilation area [m^2]	Occupation area [m^2]	Total area [m^2]
266.80	18,000	4.80×10^6	1649	4.80×10^9

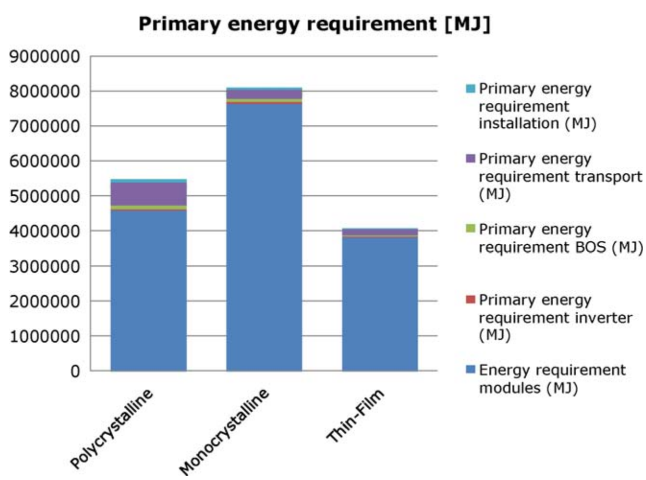

Fig. 3. Primary energy requirement [MJ].

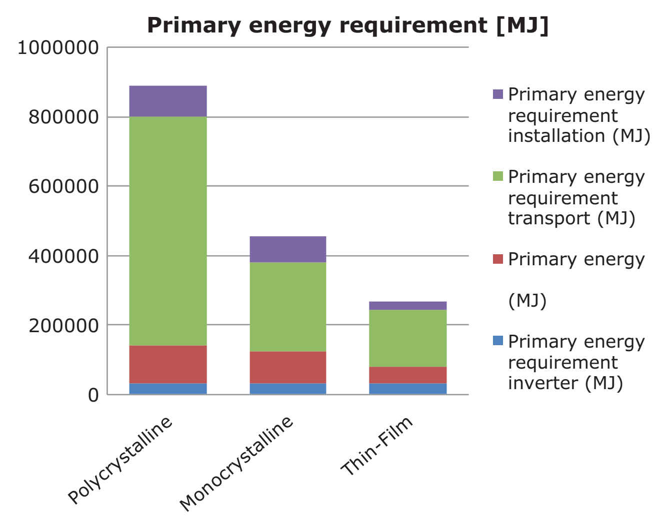

Fig. 4. Primary energy requirement.

In this case and in terms of land, the best technology would be the monocrystalline one (141.73 kWp/m^2) which, on the other hand, has a very high energy input for the manufacturing stage. In most of the cases, this is the main reason not for choosing this type of technology.

In spite of the low kWp/m^2 ratio of the thin-film technology (62.96 kWp/m^2), this is often chosen because of its placing advantages: since it is not a rigid module, it is much easier to incorporate it in the building volumes resulting in a much better visual integration.

Concerning to polycrystalline technology, this has a 139.17 kWp/m^2 ratio, which is a lower value in comparison with monocrystalline technology. This technology is often chosen because of its lower energy input.

4.3.2. *Primary energy required per stage*

As depicted in Fig. 3, the total primary energy consumption of the whole PV system consisting of the manufacture energy of the PV modules, balance of system components, and inverter in addition to the transportation and installation energy was 5.48×10^6, 8.13×10^6, 4.08×10^6 MJ in polycrystalline, monocrystalline and

Table 7
Electrical characteristics of the modules.

Technology	Polycrystalline	Monocrystalline	Thin-film
Module	Suntech STP-270-24/Vd	Suntech STP-180S	Uni-Solar PVL 136
Open circuit voltage (V_{oc})	44.5 V	44.8 V	46.2 V
Optimum operating voltage (V_{mp})	35.0 V	36.0 V	33.0 V
Short-circuit current (I_{sc})	8.20 A	5.29 A	5.10 A
Optimum operating current (I_{mp})	7.71 A	5.0 A	4.13 A
Maximum power at STC (P_{max})	270 Wp	180 Wp	136 Wp
Operating temperature	−40 °C/+85 °C	−40 °C/+85 °C	−40 °C/+85 °C
Maximum system voltage	1000 V DC	1000 V DC	1000 V DC
Maximum series fuse rating	20 A	15 A	8 A
Power tolerance	±3%	±3%	±3%

STC: irradiance 1000/m^2; module temperature 25 °C; AM = 1.5.

Table 8
Solar radiation at the different locations provided by the Meteonorm 6.1.

Location	Solar radiation (kWh/m^2)
Almería (36.5°N, 2.2°O)	1930.9
Madrid (40.5°N, 3.8°O)	1858.4
Pineda de Mar (41.4°N, 2.4°E)	1614.1
Santander (43.3°N, 4.1°O)	1408.8

thin-film, respectively. About 84, 94 and 94% of the total primary energy was consumed in the production of the PV modules.

4.3.3. *Primary energy required (w/o) modules*

Besides the energy used in the module manufacturing, the rest of stages should also be pointed out.

As shown in Fig. 4, the thin-film technology has a lower requirement due mainly to the fact that this type of technology has no subjection frame and thus the support structures are not necessary.

Regarding the transport, directly related to the modules weight, the most considerable is that of the polycrystalline modules, as they are heavier. The lighter technology is the thin-film one due to the lack of frames.

Finally, concerning to the installation must be noted that there's no need of mounting the anchorage structures for the thin-film technology. This fact benefits this type of technology because it has a lower energy requirement than in the other two cases.

4.3.4. *Sensitivity study results*

This section presents briefly the data needed to perform the simulations with PVsyst (Table 7), as well as the results of the sensitivity study. The sensitivity analysis has been carried out by modifying only one of the system variables, which is the level of incident solar radiation. Therefore, four locations with different solar radiation and with similar transport energy expenditure have been considered. Fig. 5 shows the solar radiation map of Spain [60].

As shown in Table 8, one place with the bigger solar radiation within the limits of the Spanish geography is Almería. Next places chosen for the sensitivity study are Madrid and Pineda de Mar with lower solar radiation values. Finally, the last location is Santander, with the lowest solar radiation value included in the study.

Two Ingecom 100 inverters have been used for each technology in order to perform the DC/AC conversion.

4.3.4.1. Energy payback time. The values obtained related to the energy payback time have been associated with the incident radiation for each location, once all the simulations and calculations have been realized. A linear equation for each type of technology has been obtained.

The plots that relate modules manufacturing energy payback time with radiation at each location are included next (Figs. 6–8), which show the results of varying only the radiation factor.

- Polycrystalline technology, Fig. 6.
- Monocrystalline technology, Fig. 7.
- Thin-film technology, Fig. 8.

It can be seen from Figs. 6–8 a strong trend on the decrease of the energy payback time due to an increased radiation. This confirms the hypothesis that more energy is produced when radiation is higher and, therefore, the time the installation is profitable will be lower.

Furthermore, it can be observed a slight trend for the stabilization of the energy payback time at very high values of solar radiation.

Table 9
Collection of line regression equations.

Technology	Obtained equations for the modules
Polycrystalline	$y = -0.002x + 8.380$
Monocrystalline	$y = -0.004x + 16.38$
Thin-film	$y = -0.002x + 7.327$

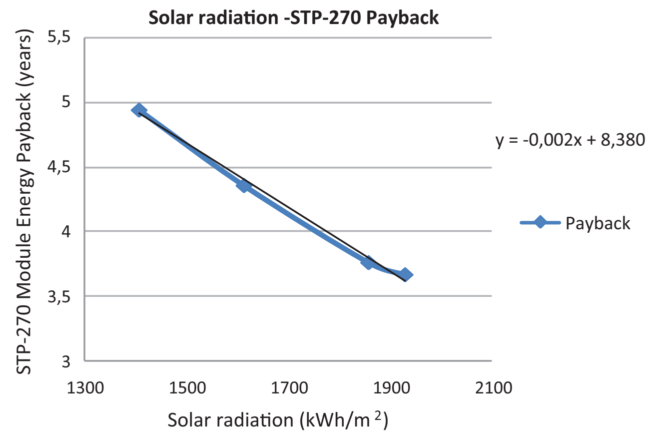

Fig. 6. Relation between the solar radiation with the energy payback time for polycrystalline technology modules (STP270), x = solar radiation (kWh/m^2), y = EPBT.

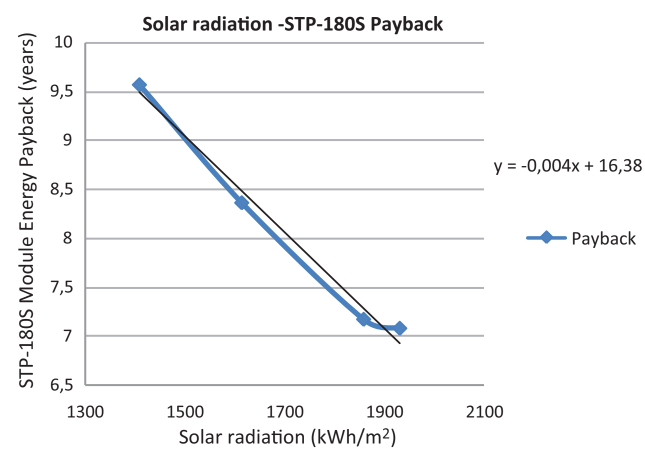

Fig. 7. Relation between the solar radiation with the energy payback time for monocrystalline technology modules (STP180S), x = solar radiation (kWh/m^2), y = EPBT.

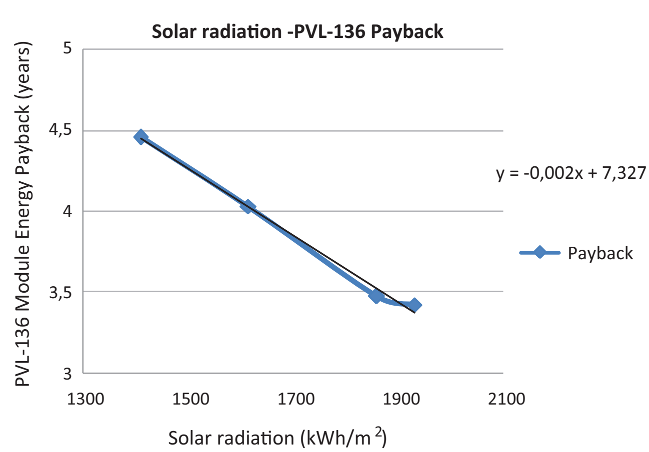

Fig. 8. Relation between the solar radiation with the energy payback time for thin-film technology modules (PVL-136), x = solar radiation (kWh/m^2), y = EPBT.

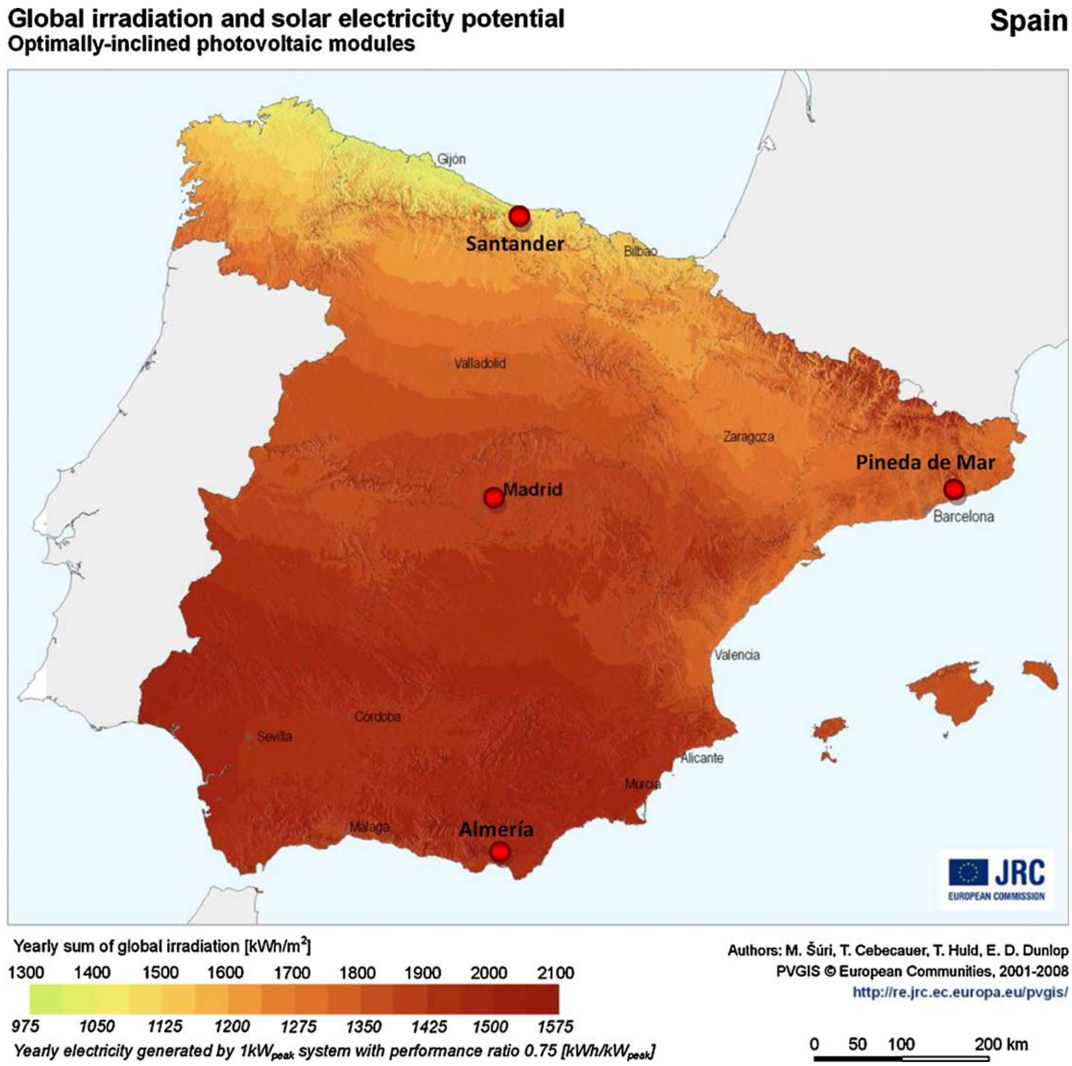

Fig. 5. Solar radiation map of Spain and situation of the locations considered [60].

Table 10
Relation between radiation and the energy payback time in years.

	Solar radiation (kW/h)	Polycrystalline technology	Monocrystalline technology	Thin film technology
Almería	1930.9	3.67	7.08	3.43
Madrid	1858.4	3.76	7.17	3.48
Pineda	1614.1	4.36	8.37	4.03
Santander	1408.8	4.94	9.57	4.45

The equations in Table 9 have been obtained taking the solar radiation as the independent variable and the energy payback time as the dependent one.

Thus, as shown in these equations, the energy payback time is inversely proportional to the existing solar radiation at each location.

Table 10 shows the relation between the solar radiation and the energy payback time for the different technologies modules.

5. Conclusions

A life cycle analysis of a polycrystalline technology photovoltaic system located in Catalonia has been performed, evaluating the greenhouse gas emissions and the energy payback time.

According to the criteria air pollutants, the manufacturing life cycle stage of the photovoltaic modules exerted the highest environmental impact potential (air emissions) among all stages and components of the whole PV system.

Regarding the energy required per stage, the production of the PV modules consumed more than the 84% of the total primary energy consumption of the whole PV system.

A sensitivity study has been performed modifying the level of solar radiation, considering four different locations with similar transport energy expenditure. It has been seen a strong trend on the decrease of the energy payback time due to an increased radiation, as well as a slight trend for its stabilization at very high values of solar radiation. In addition, the energy payback time is inversely proportional to the existing solar radiation at each location.

In the current location the life cycle analysis for the polycrystalline photovoltaic modules provides an energy payback time of 4.36 years. The energy pay-back time for the modules when using polycrystalline technology varies from 3.67 years in Almería to 4.94

years in Santander, which corresponds to the worst case. Considering the monocrystalline technology, the results vary from 7.08 to 9.57 years in Almería and Santander, respectively. Finally, the thin-film technology has an energy payback time of 3.43 years in Almería and 4.45 years in Santander, values very similar to the polycrystalline technology.

To conclude this study, PV technology offers a significant potential for energy savings and CO_2 mitigation. Although the energy pay-back time for the current systems is still relatively high, especially for monocrystalline silicon modules, it is generally lower than their expected life time, usually between 20 and 30 years.

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